*33rd EPS Conference on Plasma Phys. Rome, 19 - 23 June 2006 ECA Vol.**30I**, P-5.034 (2006)*

Optical transitions of highly charged ions in high density laser produced plasmas

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Abstract

Optical transitions of dense Al laser produced plasmas have been investigated in the out-streaming plasma jet. A strong emission from line transitions originating from several charge states (Li-like until Ne-like, spectral range 450 – 550 nm) is observed. Spectra simulations which employ ab inito atomic structure calculations have been established. The simulations demonstrate the potential use of optical spectra of highly charged ions in dense plasmas to determine the charge state distribution. On the basis of Zeeman-Stark simulation we discuss also the possible application for magnetic field measurements.

I. Introduction

Since the publication of the first monograph on plasma spectroscopy [1], spectroscopic methods have provided essential information about basic plasma parameters and relevant physical processes. The accessible parameter range covers orders of magnitude ion temperature and (especially) density, because practically all elements of particular, selected isoelectronic sequences can be used for diagnostics. These elements may occur as intrinsic impurities or may be intentionally injected in small amounts. Detailed reviews of spectroscopic methods have been published since [2-4].

In hot plasmas (e.g.: magnetic and inertial fusion, high energy laser produced plasmas, high current Z-pinches), x-ray line transitions from single and double excited states of highly ionized ions are usually employed for plasma diagnostics whereas optical transitions are rarely considered. In the present work, we report about an experimental campaign [5] at the PALS laser facility [6] to investigate optical transitions from highly charged ions in a plasma.

II. Experimental setup

Figure 1 shows the scheme of the experimental setup. A 20 μm thick Al foil has been irradiated with a 56 J laser beam at 3 omega (λ = 438 nm) and a focal spot diameter of 80 μm. The pressure in the target chamber was $p = 7\cdot 10^{-1}$ mbar. The laser beam was directed normal to the target surface. The line of sight of the Oriel Instruments Imaging Spectrometer MS260i (2 gratings: 150 l/mm blazed at 800 nm, 1200 l/mm blazed at 350 nm) was perpendicular to the outgoing plasma jet. In order to depress background radiation (stray light), a 20 cm long tube made of black aluminium was installed onto optics of the fiber cable and on the opposite side a black screen was setup. The images were taken single shot using CCD detection system, with a gate pulse width of 500 ns, and an exposure time of 0.017 s. The spectral resolution was estimated to be about 0.1nm.

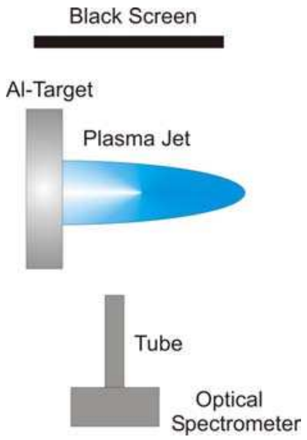

Figure 1: Schematic setup of the optical spectrometer

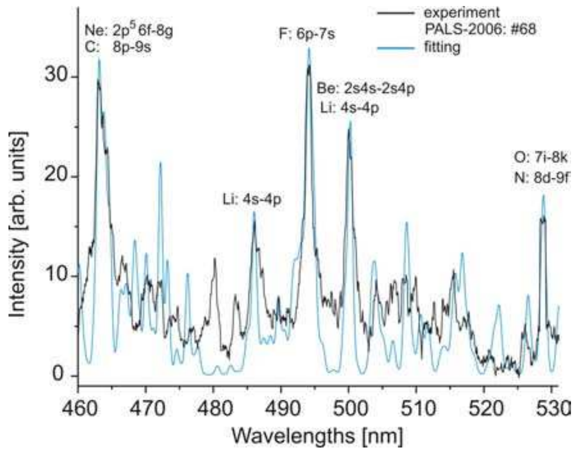

Figure 2: Experimental spectrum (black curve) from aluminium. Some line transitions are indicated. The blue curve shows a fitting (see text).

Figure 2 shows the experimental spectrum of aluminium in the wavelengths interval 460 – 530 nm. Some identified line transitions from Li-,.. Ne-like Al ions are indicated.

III. Simulations of optical transitions

Due to the multitude of line transitions in the optical wavelengths range of highly charged ions, the line identification requests a spectra simulations. We therefore have performed ab initio atomic structure calculations employing the HFR-code [7] in a multi-configuration interaction calculations including intermediate coupling and relativistic effects.

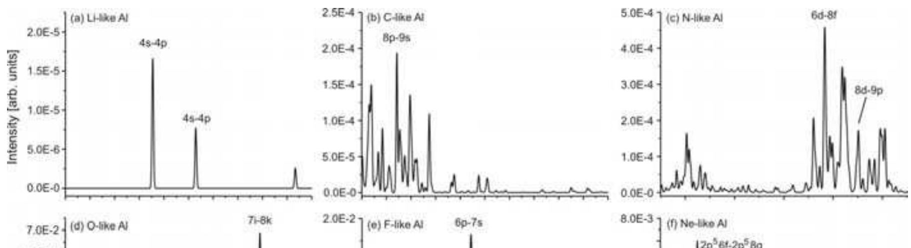

Figure 3: Theoretical spectra (F_{ji}=1) of aluminum originating from various

Figure 3 shows the spectral distribution for various charge states according

$$I(\omega)=\sum_{k=1}^{Zn} f_k \sum_{i,j\in k}^{N} g_j\, A_{ji}\, \Phi_{ji}\left(\omega,\omega_{ji}-\Delta_k\right)F_{ji}\,. \qquad (1)$$

g_j is the statistical weight of the upper level, A_{ji} the spontaneous transition probability for a bound-bound transition $j\rightarrow i$, Φ_{ji} is the line profile, F_{ji} is an excitation function, f_k is the ionic fraction (e.g;, k=10 corresponds to Ne-like Al) and Δ_k is a line shift. It is seen, that numerous transitions of one charge stage overlap, however, they accumulate in a narrow wavelengths interval (e.g., O-, F-, Ne-like Al). Therefore, the emission from various charge states can be separated in the total spectrum. Figure 2 (blue curve) shows a spectrum fitting employing an excitation function according

$$F_{ji} = \frac{1}{g_i} \exp\left(-\Delta E_{ji} / kT\right). \qquad (2)$$

ΔE_{ji} is the energy difference between upper and lower states, g_i the statistical weight of the lower level and T is an excitation parameter. The excitation function according eq. (2) depresses transitions from high n-configurations compared to low n-configurations. The simulation shown in figure 2 (kT=20 eV) permits the identification of the most prominent emission structures. The utilisation of a genetic algorithm allowed us to determine the f_k-parameters. As the emission structures from O-, F-like and Ne-like Al ions are composed from similar high lying configurations n=7, 8, the fitting of the f_k-factors permits to estimate some relative ionic fractions: f(O):f(F):F(Ne) = 1:0.24:0.18.

The inspection of atomic data bases has shown, that complete sets of transition probabilities/wavelengths are not available. Therefore, simulations of the spectral distribution must largely be based on the capability to perform ab initio atomic structure calculations with reasonable accuracy. The inspection of atomic data from various calculations we have performed shows, that the wavelengths accuracy of optical transitions is rather limited.

In order to estimate the data accuracy for the present simulation approach, we have also inspected the records of several data bases. The situation turns out to be not very satisfactory. Even for the simplest configurations and transitions, the indicated wavelengths differ largely. Table 1 shows one example for the Li-like Al ions: $1s^2 4s\ ^2S_{1/2} - 1s^2 4p\ ^2P_{1/2,3/2}$. The NIST database [8] provides energy levels which result in wavelengths differences from the relativistic-many-body-perturbation-theory benchmark calculation (RMBPT*[a]) by more than 15 nm, whereas the HFR* calculation differ from these values only by about 0.3 nm. The wavelengths differences from different J-levels is in reasonable agreement.

Table 1: *Wavelengths of the Li-like $4s_{1/2}$–$4P_{1/2,3/2}$ transitions obtained from present calculations (*=configuration interaction+intermediatie coupling, configuration up to $1s^2nl$ with n=10, l=0-9 are included, HFR [7]: relativistic wave-function correction, FAC [9]: n=2,3 optimized, a=Dirac-Fock + Breit + correlation + polarisation + red.mass, b=Dirac-Fock only) and data bases NIST [8] and W3 [10] (a=Edlen semi-empirical, b=Edlen theory, c=Knight, d=Vainshtein).*

Li-like Al	HFR*	FAC*	**RMBPT* a**	RMBPT* b	NIST	W3(a)	W3(b)	W3(c)	W3(d)
$4p_{3/2}$-$4s_{1/2}$	485.2	489.7	**485.6**	482.9	471.5	487.1	486.6	492.1	475.2
$4p_{1/2}$-$4s_{1/2}$	502.7	506.9	**503.1**	501.6	489.7	504.9	504.9	492.1	492.2
ΔJ	17.5	17.2	**17.5**	18.7	18.2	17.8	18.3	0.0	17.0

For spectra simulations, a wavelengths accuracy of at least 1 nm in the optical range is requested. Allowing the genetic algorithm to find non-zero shifts Δ_k, the fitting can be improved. For the simulations of figure 2, e.g., we obtain, e.g., $\Delta_{O\text{-like}}$= - 0.24 nm, $\Delta_{F\text{-like}}$= - 0.08 nm, $\Delta_{Ne\text{-like}}$= - 1.22 nm.

IV. Combined Zeeman-Stark effect

The investigation of magnetic field in dense laser produced plasmas is of large interest to provide information about the plasma jet formation [11] and enhanced confinement [12]. Optical transitions have the advantage, that magnetic field effects are much more pronounced because the relative Zeeman splitting is proportional to the wavelengths itself $\Delta\lambda_{Zeeman}/\lambda \sim \lambda$. The disadvantage of optical transitions is connected with Bremsstrahlung. However, as the present experiments have shown, it is possible to detect the optical transitions with a reasonable intensity compared to the background.

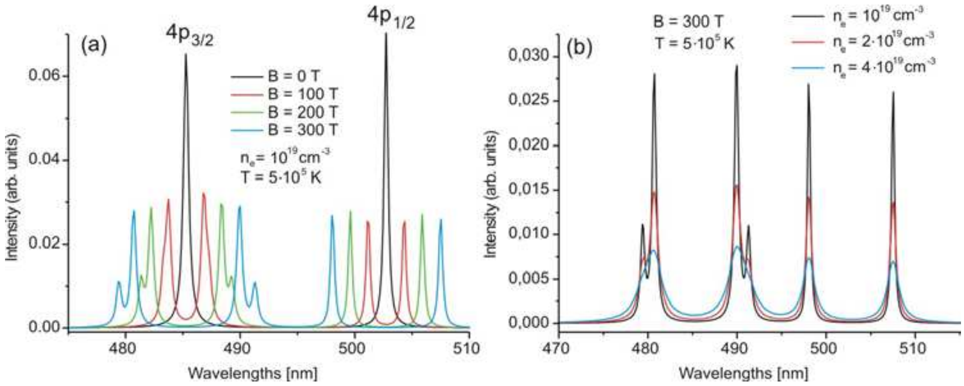

***Figure 4**: Simulations of combined Zeeman/Stark effect, Li-like 4s-4p transitions of Al*

Figure 4 shows Zeeman/Stark simulations [13] of the observed Li-like 4s-4p transitions. It can be seen, that magnetic field effects can be easily resolved. The adavantage of the utilisation of transitions with different total angular momentum J is, that Stark and Zeeman effects can be directly separated, because the Landé-factor depends on J whereas the Stark-broadening is essentially independent of J.

Acknowledgement
Support from LASERLAB EUROPE under contract number PALS 1080 and from INTAS 03-54-6348 is greatly acknowledged.

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